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MAXIMUM ALLOWABLE CONCENTRATION FOR AIR-BORNE BETA CONTAMINATION

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A B S T R A C T

By comparing the damage produced by beta particles and uranium alpha particles emitted by material uniformly distributed in the lungs, an equation was derived by which the maximum allowable concentration in the atmosphere of a beta-emitting isotope for which lung damage is the limiting consideration can be calculated. It was calculated that for such isotopes a conservative value for the maximum allowable concentration is 20 counts per minute per ft.3 as measured by the counter presently in use at K-25 for air sample beta counting.

The equation for calculating the maximum allowable concentration for beta emitters which are retained in the body and for which lung damage is not the limiting consideration is given. As examples of the use of this equation, maximum allowable air-borne concentrations as determined by retention in the body were calculated for Sr^{89}, Sr^{90}, and UX_1. An equation for the maximum allowable concentration of an isotope for which body retention is the limiting factor, in combination with isotopes for which lung damage is the limiting factor was derived. A curve is given which shows the maximum allowable counting rate for Sr^{90} in combination with other beta emitters having an average energy of 0.4 Mev., as a function of the fraction of the disintegrations due to Sr^{90}.

MAXIMUM ALLOWABLE CONCENTRATION FOR AIR-BORNE BETA CONTAMINATION

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MAXIMUM ALLOWABLE CONCENTRATION FOR AIR-BORNE BETA CONTAMINATION

INTRODUCTION

For many beta-emitting isotopes, the determining factor in establishing a maximum allowable value for air-borne contamination is radiation damage to the lungs. The maximum allowable concentration of these isotopes in the atmosphere can be calculated from the similar concentration for uranium by comparing the damage produced by the uranium uniformly deposited in the lungs with the damage produced by an equal activity of the beta emitter. In this report, the present K-25 maximum allowable concentration of uranium in the atmosphere was used to calculate a value for beta emitters for which lung damage is the principal consideration.

For isotopes which are selectively deposited in various organs, damage to a particular organ may be the determining factor; for such isotopes, a value for the maximum allowable concentration can be calculated by standard methods on the basis of the elimination rate from the body and the maximum allowable concentration in the body.[1] For applications to health physics monitoring of air-borne activity, it is convenient to express the maximum allowable concentration in terms of a counting rate with a particular instrument, and since the counting efficiency is a function of the energy, the maximum allowable counting rate will also be a function of the energy. When the activity consists of a mixture of an isotope such as Sr^{90}, for which the maximum allowable counting rate is low, with other beta emitters, the maximum allowable counting rate will depend both on the ratio of Sr^{90} activity to total beta activity and on the counting efficiencies for the various isotopes. With any particular mixture of isotopes, the counting efficiency will be constant and if Sr^{90} is combined with such a mixture of isotopes, the maximum allowable counting rate for the combination will be a function of the ratio of Sr^{90} activity to the total activity.

GENERAL CONSIDERATIONS

When a radioactive isotope is inhaled, the amount of the isotope which accumulates in the body is dependent on the following factors:

1. Concentration of the isotope in the air.
2. Breathing rate.
3. Fraction of the isotope inhaled which is not immediately exhaled.
4. The fraction of the isotope trapped in the lungs which is absorbed by the blood stream.
5. The fraction of the isotope which is fixed in the body before it is eliminated from the body.
6. The radioactive decay constant.
7. The biological elimination constant of material which has been fixed in the body.

1 For example see Perry, C. H., Internal Dose Determination of Several Radioisotopes, February 27, 1950 (ORNL-591)

ISOTOPES FOR WHICH LUNG DAMAGE IS THE PRINCIPAL CONSIDERATION

Assumptions

The assumptions made in calculating a maximum allowable air-borne concentration for beta emitters on the basis of radiological damage to the lungs only are as follows:

1. Insoluble compounds of a radioactive isotope are removed from the lungs more slowly than are soluble ones and are thus more hazardous from the standpoint of lung damage.
2. Insoluble compounds, whether β or α active, are deposited in the lungs and eliminated therefrom in the same way as insoluble uranium compounds.
3. The relative biological effectiveness (RBE) of alpha particles is 10.
4. The fraction of material retained in the lungs and its biological half-life are independent both of the isotopic concentration and of its concentration in the atmosphere.
5. Radiation to the lungs as a result of inhaled uranium will not exceed the maximum allowable weekly dose of 300 mrem if the K-25 maximum allowable air-borne concentration of uranium is not exceeded.
6. Material which is retained in the lungs is uniformly deposited throughout the lungs.

Calculation of Maximum Allowable Concentration of Beta Activity from Alpha Value

At the central portion of the lungs, the ionization produced per gram of tissue by uniformly distributed activity is directly proportional to the energy of the radiation and is independent of the nature of that radiation, provided the distance from the center of the lungs to the periphery of the lungs is greater than the range of the radiation, for, in this case, the central portion will be effectively in an infinite medium and the energy absorbed per gram of tissue will be equal to the energy radiated per gram of tissue.

The most energetic beta radiation considered is the 3.55 Mev. beta of Rh^{106} which results from beta decay of Ru^{106}. From information concerning the range of beta particles as a function of the density of material[2] and the known density of the lungs[3] of 0.18 g./cm.3, it is found that the range of 3.55 Mev. beta particle in the lung is approximately 10 cm. The central portion of the lung, as found by measurement of X-ray photographs, is approximately 11 cm. from the periphery of the lung; thus, at the central portion of the lung, the energy absorbed per gram of tissue is equal to the energy radiated per gram, and, for a given concentration of activity, the energy released per gram is directly proportional to the average energy of the radiation.

The air-borne concentration of a beta-emitter, expressed in counts/min./ft.3, which would result in the same dosage rate to the lungs as the present maximum

2 Lapp, R. E., and Andrews, H. L., Nuclear Radiation Physics, Prentice-Hall, New York

3 Gray, Henry, Anatomy of the Human Body, p. 1113, Lea and Feibger, Philadelphia, 1942

allowable concentration of uranium is given by the relationship

$$C = D \frac{10 E_a e_b}{E_b}$$

where

C = maximum permissible counting rate for air-borne beta activity

D = maximum permissible disintegration rate for uranium = 6.6 dis./min./ft.^{3}

10 = relative biological effectiveness of ionization produced by alpha particles

E_a = energy of the alpha particles = 4.5 Mev.

E_b = average energy of the beta particles in Mev.

e_b = counting efficiency of the beta particles.

Thus, the maximum allowable beta counting rate is given by the relation

$$C = \frac{10 E_a e_b}{E_b} \times 6.6 = 297 \frac{e_b}{E_b} \text{ counts/min./ft.}^3.$$

The detector used at K-25 for air sample beta counting is an Eck and Krebs geiger tube having walls 37 mg./cm.^{2} thick. The tube has an outside diameter of 19.8 mm., an inside diameter of 19.6 mm., and an effective length of 70 mm. Dust samples are collected on filter papers 88 mm. in diameter and are placed below the horizontal tube at a distance of about 4.4 mm. from the tube. The efficiency for this counter is shown in figure 2 as a function of the maximum beta energy.[4] Using the equation given above and the efficiencies obtained from figure 2, the maximum allowable counting rate was calculated for beta emitters of various energies. The results are given in table I.

Since all of the values listed in the last column of table I are greater than 20 counts/min./ft.^{3}, this figure is considered to be a conservative value for the maximum allowable concentration in the atmosphere of beta emitters having maximum beta energies between 0.3 Mev. and 4.0 Mev. There may be some doubt of the accuracy of the counting efficiency for low energy betas, however, and this value is recommended only for beta emitters having maximum energies between 0.5 and 4.0 Mev., or average energies between 0.15 and 1.2 Mev.

4 Knight, G. B., Letter to H. F. Henry concerning the efficiency of beta counters for air samples as related to the beta energy.

TABLE I

MAXIMUM ALLOWABLE COUNTING RATE FOR AIR-BORNE BETA ACTIVITY

E_{max} Maximum Beta Energy	$\bar{E}$ Average Beta Energy ($\sim$ 0.3 E_{max})	e_b $\bar{E}$ Beta Counting Efficiency	Maximum Allowable Beta Counting Rate
0.3	0.09	0.009	29.7
0.5	0.15	0.021	41.5
1.0	0.30	0.048	47.5
1.5	0.45	0.066	42.5
2.0	0.60	0.077	38.1
2.5	0.75	0.082	32.5
3.0	0.90	0.088	30.4
3.5	1.05	0.092	26.0
4.0	1.20	0.095	23.5

MAXIMUM ALLOWABLE AIR-BORNE CONCENTRATION OF AN ISOTOPE WHICH BECOMES FIXED IN THE BODY

The rate of change of the quantity of an isotope in the body is given by the relation:

$$\frac{dN}{dt} = F - N(\lambda_R + \lambda_B) \qquad \text{(Eq. 1)}$$

where

F = rate of fixation of the isotope in the body, which is proportional to the rate of intake

N = amount of isotope present at a given time

λ_R = radioactive decay constant = $\frac{0.693}{T_R}$ where T_R = radioactive half-life of the element concerned.

λ_B = biological elimination constant from the body = $\frac{0.693}{T_B}$ where T_B = biological half-life of the element concerned.

The solution of equation 1 is:

$$N = \frac{F\left[1 - e^{-(\lambda_R + \lambda_B)t}\right]}{\lambda_R + \lambda_B} \qquad \text{(Eq. 2)}$$

If F is constant, then the maximum concentration or equilibrium value of the isotope will occur when $t = \infty$ or $N = \frac{F}{\lambda_R + \lambda_B}$. If the equilibrium value is

made equal to the maximum allowable concentration (M) of the isotope in the body, the corresponding maximum allowable value of the feed rate, F, can be found.

$$N = M = \frac{F}{\lambda_R + \lambda_B} \qquad \text{(Eq. 3)}$$

or

$$F = M(\lambda_R + \lambda_B) = M\left[\frac{0.693}{T_R} + \frac{0.693}{T_B}\right] \qquad \text{(Eq. 4)}$$

The feed rate into the body, F, will be:

$$F = Q\ R\ K_1\ K_2 \qquad \text{(Eq. 5)}$$

where

Q = concentration of the isotope in air in $\mu c./ft.^3$

R = breathing rate

K_1 = fraction of isotope trapped in lung and absorbed by the blood

K_2 = fraction of isotope in blood which is fixed in the body.

Since

$$Q\ R\ K_1\ K_2 = F = 0.693\left[\frac{1}{T_R} + \frac{1}{T_B}\right],$$

$$Q = \frac{0.693\ M}{R\ K_1\ K_2}\left[\frac{1}{T_R} + \frac{1}{T_B}\right]. \qquad \text{(Eq. 6)}$$

As examples the maximum allowable concentrations in the atmosphere of Sr^{89}, Sr^{90}, and UX_1, all bone-seekers, were calculated with this equation by use of the data listed in table II. Sr^{89} and UX_1 are retained in the body but the limiting consideration for both of these is found to be lung damage, whereas the limiting consideration for Sr^{90} is bone damage.

TABLE II

CONSTANTS FOR CALCULATING MAXIMUM ALLOWABLE AIR-BORNE CONCENTRATION

Isotope	Beta Energy[5]	Radioactive[5] Half-life	Biological Half-life	Max. Allowable Concentration in Body[6]	Beta Counting Efficiency
S^{90} ↓	0.6	25 yr.	1000 days	1μc. Sr^{90} in Equilibrium with Y^{90}	2.5%
Y^{90} ↓	2.35	65 hr.			8.25%
Zr^{90}	Stable				
S^{89} ↓	1.5	53 days	1000 days	2 μc.	6.5%
Y^{89}	Stable				
UX_1 ↓	0.20	24.5 days		1 μc. UX_1 in Equilibrium with UX_2	0.0%
UX_2 ↓	2.32	1.14 min.			8.1%
U-234	No beta	2.35×10^5 yr.			

STRONTIUM

Experimental data on the retention of air-borne particulates in the lung indicate that about 50% of the small particles which are inhaled are retained by the lung,[7] and metabolism studies indicate that about 50% of the strontium absorbed into the blood stream is eliminated from the body in about 6 days.[8]

It is not known how the continued presence of strontium in the blood stream

5 Seaborg, G. T., and Perlman, I., Table of Isotopes, Reviews of Modern Physics, Vol. 20, No. 4, October 1948

6 Morgan, K. Z., Minutes of the Subcommittee on Permissible Internal Dose of the National Radiation Protection Committee, February 9, and 10, 1950 in Washington, D. C., March 7, 1950

7 Landahl, H. D., and Tracewell, T. N., On the Retention of Air-Borne Particulates in the Human Lung, University of Chicago Toxicity Laboratory, Quarterly Progress Report No. 5 on Radiobiology, April 15, 1950

8 Sullivan, M. F., et. al., Metabolism and Toxicity of Radioactive Metals, University of Chicago Toxicity Laboratory, Quarterly Progress Report No. 5, on Radiobiology, April 15, 1950

will effect the deposition of strontium into the bone. Hamilton[9] gives experimental data which indicate that deposition of strontium in the body is less than 50% for adult rats with a high calcium intake and that the half-life is approximately 200 days. If the metabolic rate of the rat is 5 times that of man, the biological half-life in man would probably be about 1000 days.[9]

In view of these experimental data, the following assumptions were made in the calculations:

1. Fifty per cent of the inhaled Sr isotope is trapped in the lung.
2. All of the isotope trapped in the lung is absorbed by the blood stream.
3. The breathing rate is 283 ft.^{3}/8 hr. day (1 m.^{3}/hr.).[10]
4. Fifty per cent of the isotope which enters the blood stream is deposited in the body.
5. The biological elimination rate of strontium fixed in the body is proportional to the amount present and has a biological half-life of 1000 days.

Sr^{89}

Substituting the values from table II for Sr^{89} into equation 6, the maximum allowable concentration is found to be

$$Q = \frac{0.0693}{283 \times 0.5 \times 0.5} \times 2\left(\frac{1}{53} + \frac{1}{1000}\right) = 3.9 \times 10^{-4}\ \mu c./ft.^3.$$

The corresponding disintegration rate[11] is 866 dis./min./ft.^{3} and with an efficiency of 6.5% the counting rate is

$$C_{Sr^{89}} = 866 \times 0.065 = 56\ \text{counts/min./ft.}^3.$$

Since the maximum allowable value for Sr^{89} on the basis of an accumulation in the body is greater than the maximum allowable value for an air-borne beta emitter based upon lung damage, the value of 20 counts/min./ft.^{3} provides an adequate limit for Sr^{89}.

Sr^{90}

Substituting the values from table II for Sr^{90},

$$Q = \frac{0.693}{283 \times 0.5 \times 0.5}\left(\frac{1}{25 \times 365} + \frac{1}{1000}\right)\mu c./ft.^3 = 1.09 \times 10^{-5}\ \mu c./ft.^3.$$

9 Hamilton, J. G., The Metabolism of Fission Products and the Heaviest Elements in Rats and Plants, June 11, 1947 (MDDC-1180)

10 Advances in Biological and Medical Physics, p. 282, Academic Press, N. Y., 1948

11 This is equivalent to $1.4 \times 10^{-8}\ \mu c./cm.^3$, which is in good agreement with the preliminary value of $2 \times 10^{-8}\ \mu c./cm.^3$ suggested by the Subcommittee on Internal Dose of the National Committee on Radiation Protection.

The corresponding disintegration rate[12] is 2.42 dis./min./ft.^{3} and since Y^{90} was assumed to be in equilibrium with Sr^{90}, the Y^{90} disintegration rate will also be 24.2 dis./min./ft.^{3}.

The values in dis./min./ft.^{3} are converted into beta counts per minute per ft.^{3} by multiplying by the counting efficiency; the counting rates are

$$C_{Sr^{90}} = 24.2 \times 0.025 = 0.60 \text{ counts/min./ft.}^3$$

$$C_{Y^{90}} = 24.2 \times 0.0825 = 2.0 \text{ counts/min./ft.}^3$$

Thus,

$$C_{(Sr^{90} + Y^{90})} = 2.6 \text{ counts/min./ft.}^3.$$

Mixture of Sr^{90} with Other Beta Emitters

When air-borne beta activity consists of a mixture of Sr^{90} with isotopes for which lung damage is the limiting consideration, the maximum permissible counting rate depends upon the fraction of the total disintegration rate which is due to Sr^{90}.

The fraction of the total disintegrations which may be due to Sr^{90} and not exceed the maximum allowable concentration for Sr^{90} is calculated below:

Let

C_S = beta counting rate due to Sr^{90}

C_Y = beta counting rate due to Y^{90}

C_{SY} = total counting rate due to Sr and Y

C_T = total counting rate

C_R = total beta counting rate excluding counts due to Sr^{90} and Y^{90}

f = fraction of total disintegrations due to Sr^{90}

D = total disintegration rate

e_S = counting efficiency for Sr = 0.02

e_Y = counting efficiency for Y = 0.08

e_R = average beta counting efficiency for all other beta particles.

Since Sr^{90} and Y^{90} are assumed to be in equilibrium, their disintegration rates are equal and

$$C_{SY} = (e_S + e_Y) fD$$

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12 This is equivalent to 3.8×10^{-10} μc./cm.^{3} which is in reasonable agreement with the figure 2×10^{-10} μc./cm.^{3} suggested by the Subcommittee on Internal Dose of the National Committee on Radiation Protection

$$C_R = e_R D (1 - 2f)$$

$$\frac{C_R}{C_{SY}} = \frac{e_R D(1 - 2f)}{(e_S + e_Y)fD} = \frac{e_R (1 - 2f)}{(e_S + e_Y)f}$$

$$C_R = C_{SY} \frac{e_R (1 - 2f)}{(e_S + e_Y)f}$$

$$C_T = C_R + C_{SY} = C_{SY} \left[\frac{e_R (1 - 2f)}{(e_S + e_Y)f} + 1.\right]$$

As an example, let it be assumed that the average beta counting efficiency for all beta emitters present, excluding Sr^{90} and Y^{90}, is 6%, which is the counting efficiency for a beta emitter having a maximum energy of 1.3 Mev. and an average energy of approximately 0.4 Mev. By substituting the efficiencies and the value 2.6 counts/min./ft.^{3} for C_{SY}, the maximum total counting rate (C_T) which may exist without exceeding the maximum allowable concentration for Sr^{90} may be found for any given value of f.

$$C_T = 2.6 \left[\frac{0.06 (1 - 2f)}{0.1 f} + 1\right]$$

$$= \frac{1.56}{f} - 0.52.$$

By setting $C_T = 20$, the percentage of the total activity which can be due to Sr^{90} and which will permit the use of the maximum allowable concentration of 20 counts/min./ft.^{3} is found to be 7.6%.

In figure 1, the maximum allowable concentration of air-borne beta activity is plotted against the fraction of the total disintegration rate due to Sr^{90}.

UX_1

The same value may be taken for the maximum allowable concentration of UX_1 in the body[13] as was used for Sr^{90}; the same assumptions were made for the UX_1 and UX_2 calculation as were used for strontium except that the radioactive half-life of UX_1 (24.5 days) is used as the effective half-life. This is equivalent to assuming an infinite biological half-life, which tends to make the results conservative. The maximum allowable concentration as given by equation 6 is

$$Q = \frac{0.693}{283 \times 0.5 \times 0.5} \left[\frac{1}{T}\right] = 3.99 \times 10^{-4} \text{ μc./ft.}^3 \text{ or } 886 \text{ dis./min./ft.}^3.$$

13 Morgan, K. Z., op. cit.

The counting efficiency for UX_1, which has a maximum beta energy of 0.20 Mev., is zero and consequently it will contribute nothing to the counting rate but it should be noted that the maximum allowable concentration for UX_1 in the body takes into account the radiation from the UX_2 daughter. The efficiency for UX_2, which has a maximum beta energy of 2.32 Mev., is 8.1% and the maximum allowable counting rate is thus

$$C = 886 \times 0.081 = 72 \text{ counts/min./ft.}^3.$$

Since this is greater than the maximum allowable counting rate for any isotope, the value of 20 counts/min./ft.^{3} provides a safe limit for UX_1 and UX_2 airborne contamination.

If uranium is deposited in the lungs, UX_1 and UX_2 will be formed as a result of alpha decay of the uranium and both the alpha and beta particles will produce radiation to the lungs. The alpha energy (4.5 Mev.) is approximately 6 times as great as the beta energy released by the UX_1 and UX_2 decay combined (0.75 Mev. average), however, and the relative biological effectiveness of alpha particles is 10 times that for beta particles; thus, for UX formed by decay of uranium in the lungs, the beta damage will be only 1/60 that of the alpha damage, and if the maximum allowable concentration for uranium itself is not exceeded, the radiation damage produced by uranium decay products will be negligible.